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Single pass laser welding with multiple spots to join four sheets in a butt-joint configuration

Morten Kristiansen[a]*, Klaus Schütt Hansen[b], Andreas Langbak[a], Sebastian Blegebrønd Johansen[a], Simon Borup Krempin[a], Mattias Døssing Hornum[a]

[a]*Aalborg University, Department of Materials and Production, Fibigerstraedet 16, Aalborg 9220, Denmark*
[b]*IPU Technology Development, Nils Koppels Alle, Bygn 404, Kgs. Lyngby 2800, Denmark*

Abstract

Laser keyhole welding is widely used in industry due to its large welding depth and low heat input. For some industrial cases it is necessary to widen the beam to cover the joint configuration, which instead results in a lower intensity and surface conduction welds. The introduction of the high-power single mode fiber laser makes it possible to deal with this problem, because the beam can be shaped into a pre-defined pattern of multiple spots shaped to the actual joint configuration. The intensity of each spot is sufficient to make a keyhole. A case with four sheets in a butt-joint configuration is used to demonstrate the principle of how to design a spot pattern which ensures weld quality in case of a single pass laser weld.

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Keywords: Beam shaping; Laser welding; Diffractive optical element; Weld geometry; Butt joining; Multispot welding

1. Introduction

For many industrial applications laser welding is a suitable technique for joining metal parts because of the low heat input, good controllability, high repeatability and high precision of the process. Traditional laser welding performs a narrow deep keyhole, and with the introduction of the high power single mode fiber laser, the keyholes can be even

* Corresponding author. Tel.: +45-9940-8938; fax: +45-9940-7110.
E-mail address: morten@make.aau.dk

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narrower. For some applications, a wider weld is required to cover a gap and to join more parts at the same time. A wider weld can be achieved by defocusing the laser beam, which will cause the welding process to change from at keyhole weld to a conduction weld. By defocusing the laser beam, the weld width and depth can only be partially controlled. A higher degree of freedom to control the shape of the weld can be achieved by splitting the laser beam up into a number of sub-beams in a pattern required for the weld geometry.

Different methods for shaping the weld profile have been investigated, and the state of the art for instance shows the achieved results. Abt (2007) and Verhaeghe (2005) have shown how the adjustment of the focus and the beam quality achieved by different lasers affect the weld quality for a single beam weld. Salminen et. al. (2012) tested the effect of dynamic beam forming of single beams by oscillation the beam when welding. Trautmann et. al. (2004) demonstrated the weld result when applying more lasers at the same time in the weld pool using a bifocal laser system. Brian et. al. (2009), Hansen et. al. (2014) and Sundqvist et. al. (2016) have worked with various types of beam shaping and have demonstrated how these affect the laser welding process.

In this experiment a single mode fiber laser was used with a diffractive optical element to split the laser beam into spots, as illustrated in Fig. 4. This spot pattern was chosen to weld the geometry, see Fig. 1, containing four stainless steel sheets which must be joined in a round seam weld. The current joining method is plasma arc welding (PAW), which takes 44 seconds with a travel speed of about 600 mm/minute. Experiments with single beam conduction welding were also conducted in order to measure the efficiency of this process with different spot sizes.

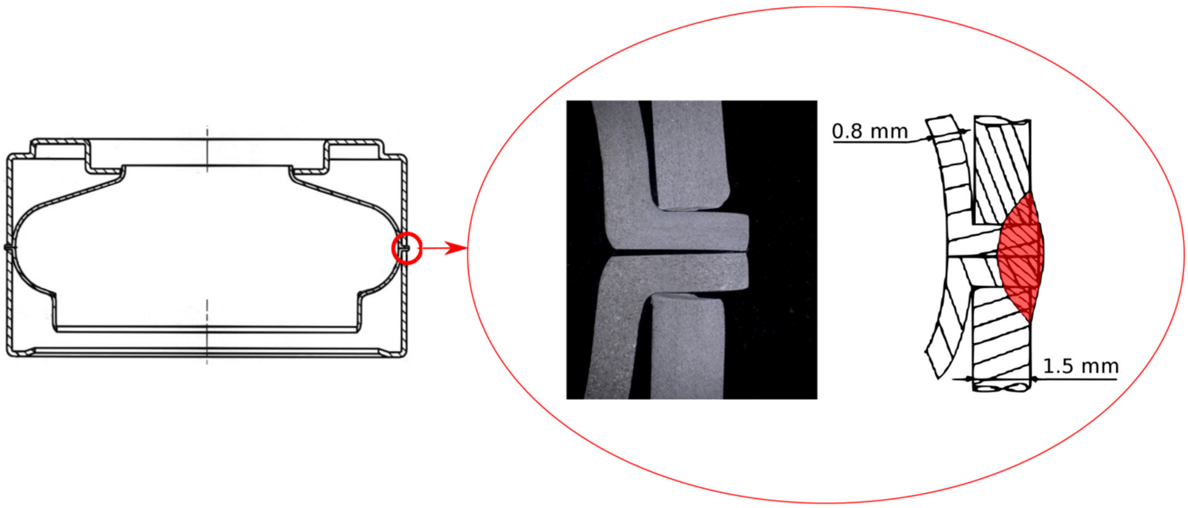

Fig. 1. Cross section of the four sheets to be joined and a magnification of the weld and the physical joining.

The process and considerations for designing a spot pattern to fulfill the welding requirements will be explored in this paper. The chosen spot pattern design will serve as a foundation to investigate the following hypotheses:

- Can the designed multispot pattern achieve the desired weld geometry and process reliability?
- Does multispot laser welding improve the process performance, thus making it possible for this to substitute the existing PAW process?

2. Spot pattern design

Design of the spot pattern must ensure that a certain weld geometry and quality are achieved for the constraints given by the sheet geometry, the available equipment and the available range of the given process variables. The spot pattern design can be based on different types of knowledge, ranging from empirical experiments to more formalised design knowledge and analytical models. Analytical models of the spot pattern effect on the weld geometry have been studied intensively for single laser beams, He X., (2012), whereas work on multispot laser, e.g. Yu-Ning Liu, (1995), is not frequently found. The design process in this work is highly based on experience from previous experiments described in Hansen et. al. (2014), Hansen et. al. (2015a) and Hansen et. al. (2015b), whose studies have evaluated the effect of different beam configurations, spot sizes and power levels. The design constraints for the spot pattern design in this work are as follows:

- Sheet geometry as shown in Fig. 2
- Welding depth of minimum 1 mm for all joints
- No welding defects (e.g. no pores, cracks etc.)
- Maximum 3 kW laser power provided by a single mode fiber laser (wavelength of 1076 nm, $M^2 = 1.2$)
- The laser head should be placed 400 mm as a minimum from the part, according to fabrication considerations
- The focus depth from the spot pattern should be at least ±2mm to achieve stability for industrial use
- The welding speed should be as fast as possible

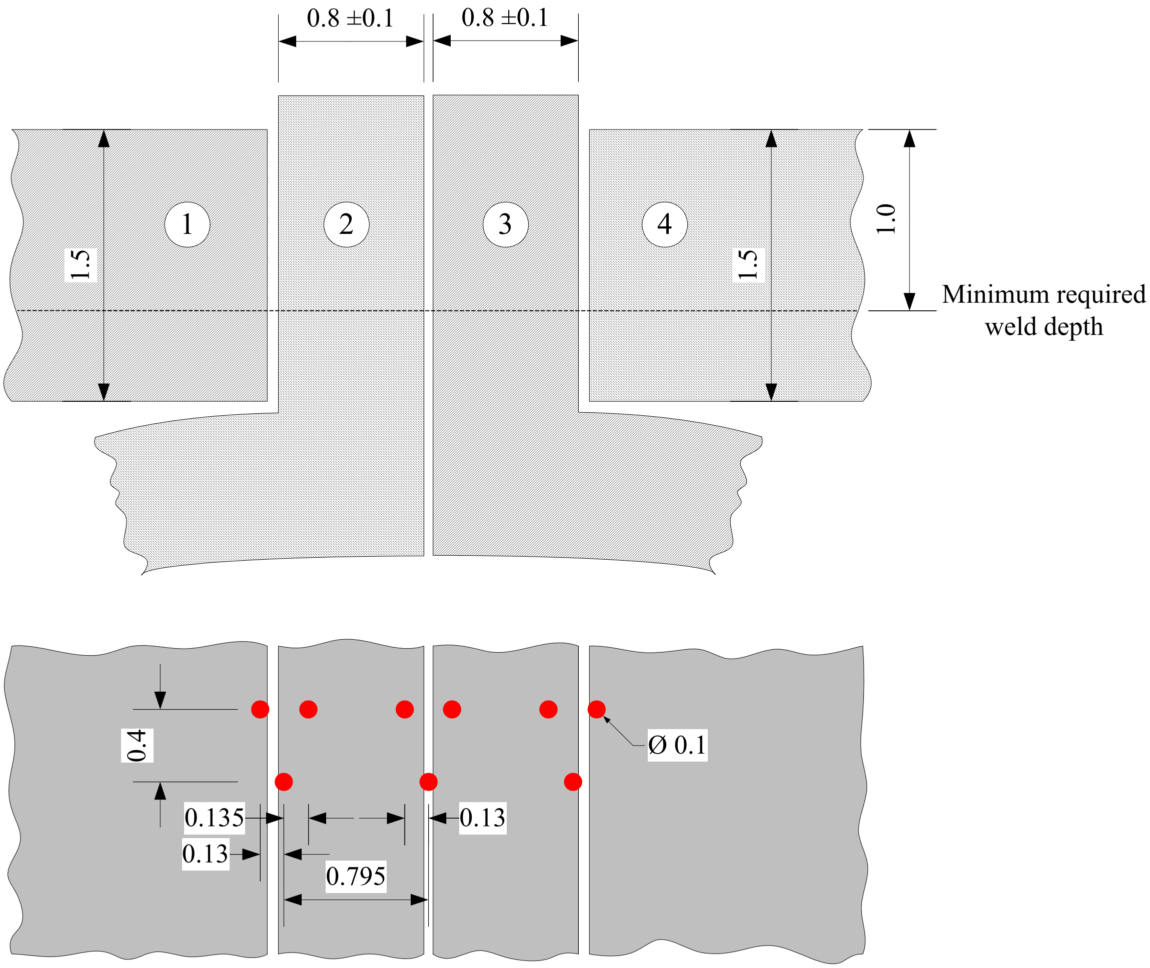

Fig. 2. Cross section at the top of the figure: Shows counter clock wise rotation of magnification in Fig. 1. The geometry to weld, where a minimum of 1 mm penetration is required in each joint. The two sheets in the middle, sheets 2 and 3, have thickness tolerances, whereas the thicknesses of the groove gap between sheets 1 and 2 and sheets 3 and 4 are unknown. Spot pattern with red dots at the bottom of the figure: Top view of the above cross section. The proposed spot pattern design with dimensions is shown on the four sheets. The pattern is symmetric over a horizontal line in the center, and the position is presented according to the above geometry to weld. All measurements are in mm.

The following aims to present the dimensions, tolerances and considerations from which the diffractive optical element (DOE) beam shape is deduced.

2.1. Tolerances

The chain of tolerances involved consists of sheet geometry tolerances, seam tracking accuracy and spot pattern accuracy.

From experience with designing and manufacturing DOE it appears that the measured tolerances of the spot pattern are 10 times better than the sheet tolerances given in Fig. 2. For this reason, the spot pattern accuracy is not considered in the tolerance chain.

The accumulated sheet geometry tolerances of the case geometry were found by calculating the worst-case dimension mismatch of thicknesses for sheets No 2 and 3 in Fig. 2, the groove gap between center sheets No 2 and 3 and the groove gap between the center sheet and the outer sheet, i.e. sheets No 1 and 2 or sheets No 3 and 4, respectively. In the industrial setup, the sheets are pressed hydraulically together before welding in order to decrease the groove gaps. This means that the actual groove gap is not known. The groove gap was not considered for this design, but further investigation of this is required.

A seam tracker must be used in order to center the laser. The uncertainty of the transverse positions of the seams relative to the spot pattern can be assumed to be ±0.05mm for linear welds, deGraaf et. al. (2010) and Luo et. al. (2012).

The overall geometrical tolerances are illustrated in Fig. 3, which does not include the groove gap tolerances. Based on this assumption, the sheet grooves will be covered by the spot pattern.

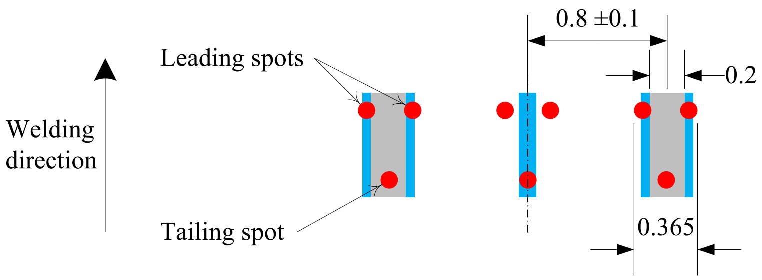

Fig. 3. Tolerance boxes are shown of the spot pattern; grey boxes show sheet tolerances, and blue boxes show the accumulated tracking tolerances.

2.2. Weld profile design

The purpose of the spot pattern is to provide deep weld penetration in the area of the three joints to achieve the required weld depth. The width of each weld has to cover the groove gap and joint tolerances when melting the excess material from the two middle sheets of the geometry into the groove gap. To achieve the deepest penetration, the smallest possible spot size must be used. The smallest spot size is dependent on the given design constraints of the available laser, as well as on focus distance and focus depth. A spot size of a maximum of Ø 0.1 mm is achievable, and this requires a minimum of 300W per spot to form a keyhole with this size, Hansen et. al. (2015a) and Hansen et. al. (2014). One keyhole per weld joint will be too narrow, which leaves the possibility of two keyholes of about 500W or three of about 333W. Due to the tolerance considerations, the spot pattern for each of the three joints must be 0.35 mm wide as a minimum. From Hansen et. al. (2015a) and Hansen et. al. (2015b) it can be deducted that two spots only in a configuration will not provide the deepest weld depth in the center of the configuration. For this reason, it was chosen to use three spots, but with a tailing spot in the center behind the leading spots, as illustrated in Fig. 3. This leaves the design with a three spot configuration for each of the three joints to be welded. The idea is that the two front spots for each joint will melt the edges and create a melt pool; afterwards the center spot will enlarge the weld pool and secure sufficient penetration of the joint. The purpose of extending the weld pool is to secure longer solidification time and solidification from the sides to avoid the occurrence of welding defects. The intensity of all spots is kept equal to secure a keyhole formation. Another purpose of the design which keeps the spots for each joint as narrow as possible is to achieve the highest possible welding speed. With this design, the variables left to control sufficient penetration are the welding speed and to some degree the focus position.

3. Experimental setup

An experimental setup was constructed to ensure that the welding experiments on the industrial sheets could be conducted at the laser laboratory at Aalborg University. The experimental setup is shown in Fig. 4, and the equipment is presented in table 1. The experiments were performed with upside down welding, and the laser beam angle was perpendicular to the workpiece.

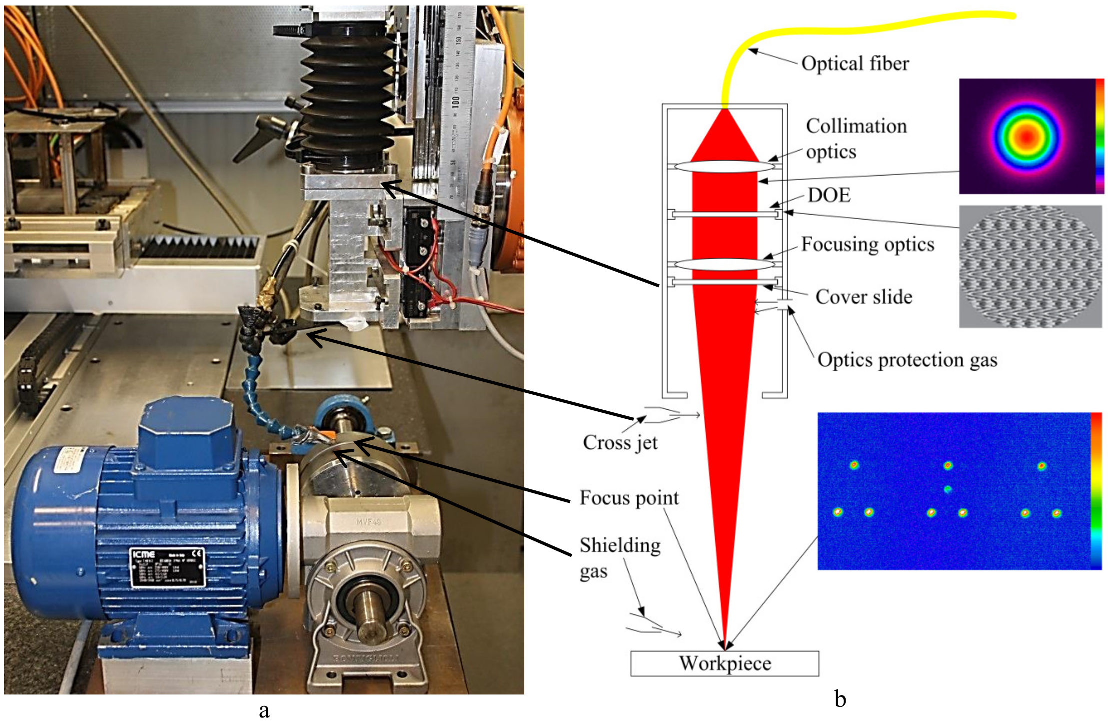

Fig. 4. (a) Physical setup; (b) schematical setup illustrating how the Gaussian laser beam passes through a DOE, forming the desired 9-spot pattern. A ghost spot with low intensity is seen at the centre of the spot pattern due to some laser light passing straight through the DOE. This is caused by manufacturing tolerances from the DOE. At the two intensity plots, the color coding scales the intensity distribution, red indicating the highest intensity.

Table 1. Equipment and settings used for all experiments.

Equipment	Type and manufacturer	Process parameters	Value
Laser	3kW IPG YLS-3000	Focal length (f_{foc})	470 mm
Processing head	HighYag 470mm focal length	Collimated beam diameter (D_0)	11.05· mm
Part turning unit	ICME non-synchronous motor T80B2 with	Beam quality factor (M^2)	1.2
	gear and a frequency converter JNEV-202-H1	Shielding gas	Mison 18
		Shielding gas flow	18 l/minute

The purpose of the experiments was to determine the travel speed, quality and stability for welding the industrial part in Fig. 1 using single beam conduction welding and including the designed spot pattern shown in Fig 2. A benchmark test will be conducted between the current PAW and the laser welding with single beam conduction and spot pattern. The process variables for PAW are not included as they only serve as references for improvement.

The material for all the sheets was AISI 304 / EN 1.4301. The process variables for the experiments are shown in Tables 2 and 3. All experiments were performed with 3000 W laser power. Initial experiments were performed to determine the process window of interest for the documented welds, which were given the following experimental ID's: C1 – C3 for the conduction welds and D1-D5 for the welds with the 9-spot pattern.

Table 2. Settings used for laser conduction welding.

Process variables	C1	C2	C3
Welding speed [mm/min]	1200	1200	1200
Focus position [mm]	146	125	103
Beam diameter ($1/e^2$ width) [mm]	3.43	2.94	2.42

Table 3. Settings used for spot pattern welding.

Process variables	D1	D2	D3	D4	D5
Travel speed [mm/min]	1357	1524	2000	2500	3000
Focus position [mm]	0	0	0	0	0

The quality of the welding experiments was evaluated by the depth of penetration at the three joints between the plates, see Fig. 5, and by examination of weld defects visible at the cut sections. To judge the stability of the process, a set of longitudinal cut sections where made to evaluate the variation of depth of penetration.

4. Results

More welds than documented were performed as the laser beam had to be centered correctly manually along the joints to perform a fusion of all four sheets. All the documented welds had a full weld around the part which and were free of visible cracks or incomplete fusion of the sheets.

4.1. PAW welding

The reference PAW weld is shown in Fig. 5.

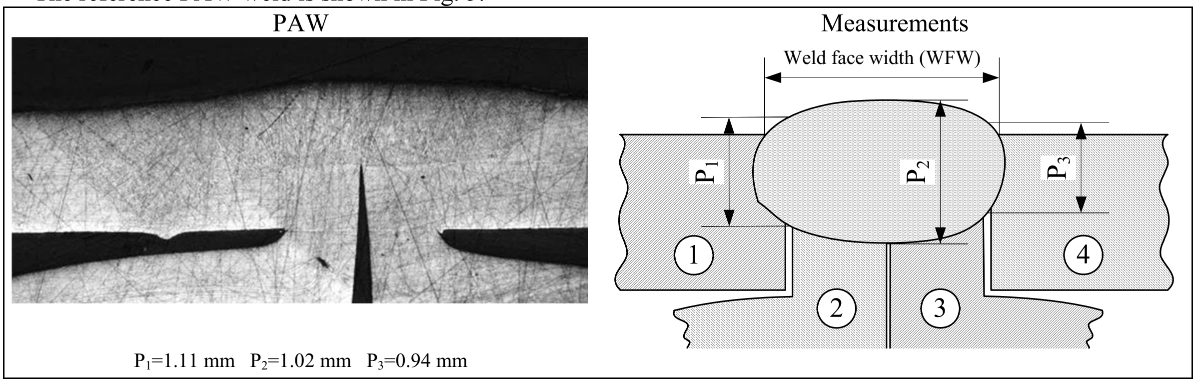

Fig. 5. Left: Cross section of the PAW reference from which the penetration was measured. Right: Definition of measurement positions. The P-values are the penetration depths in the interfaces between the sheets. The circled numbers refer to the sheets in Fig 2.

4.2. Laser conduction welding

The results of the laser conduction welds are shown in Fig. 6. Here the beam diameter was reduced from experiment C1 to experiment C3. This resulted in a reduced weld face width.

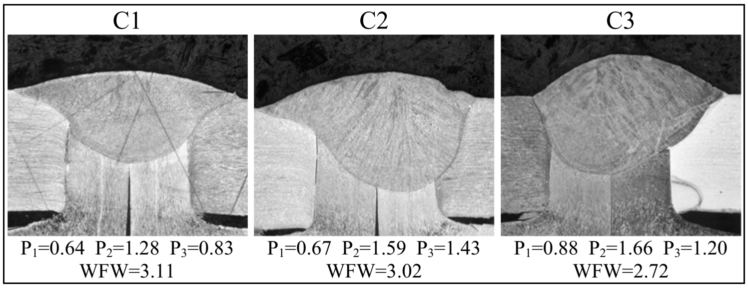

Fig. 6. Cross sections from the three conduction welding experiments showing depths of penetration and weld face width (WFW).

4.3. Spot pattern welding

The result from welding with the 9-spot pattern is shown in Fig. 7, where the travel speed was increased from experiment D1 to experiment D5. In experiment D1 and especially in experiment D2, severe porosities were observed at the bottom of the weld. Variations along the seam and between the experiments were observed. These may have been caused by trapped air in groove gaps of various sizes, problems with gas coverage or surface contamination. This problem should be examined further in future work. In Fig. 8 the stability of the weld depth is shown, and it can be visually concluded that reliable stability can be achieved by 9-spot pattern welding.

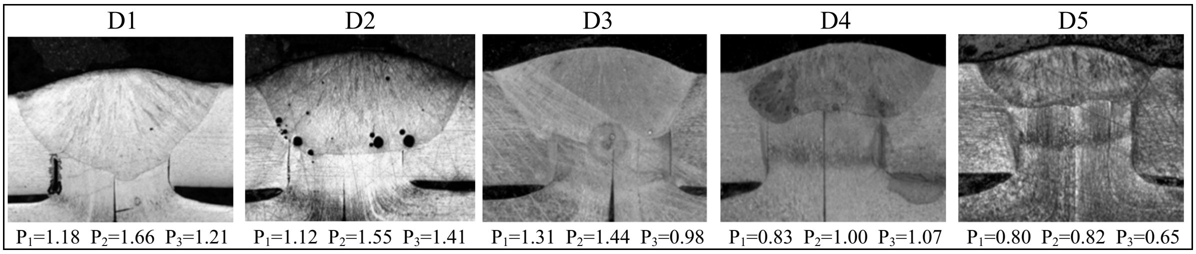

Fig. 7. The 9-spot pattern experiments with cut sections and depth of penetration.

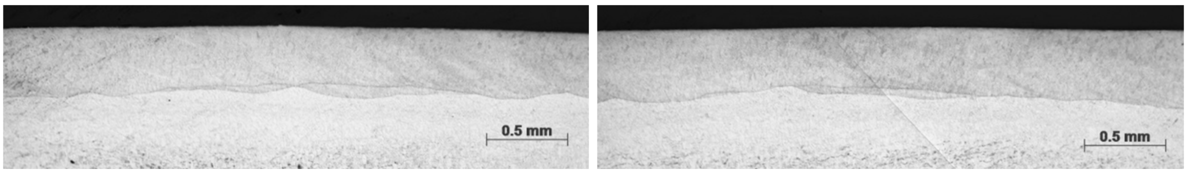

Fig. 8. Two longitudinal sections illustrating the depth of penetration. The actual location of the section in the weld cannot be determined due to the applied measurement technique.

4.4. Benchmark and discussion

For the welding methods applied, the achieved depth of penetration is shown as a function of the applied welding speed in Fig. 9. Generally, the laser welds show a higher variation in depth of penetration than PAW, and especially the variation for the conduction welds is high. For the performed welds, neither the PAW nor the conduction welds in particular satisfy the required depth of penetration. The 9-spot pattern welding achieves the required depth of penetration for travel speeds of 1357 and 1524 mm/min. Results indicate that the travel speed can be increased to between 1600 mm/min and 2000 mm/min. This leaves the possibility that if the 9-spot pattern with a 3kW single mode fiber laser is used, welding of the part can be performed at a welding speed about 3 times faster than achieved using the current PAW process.

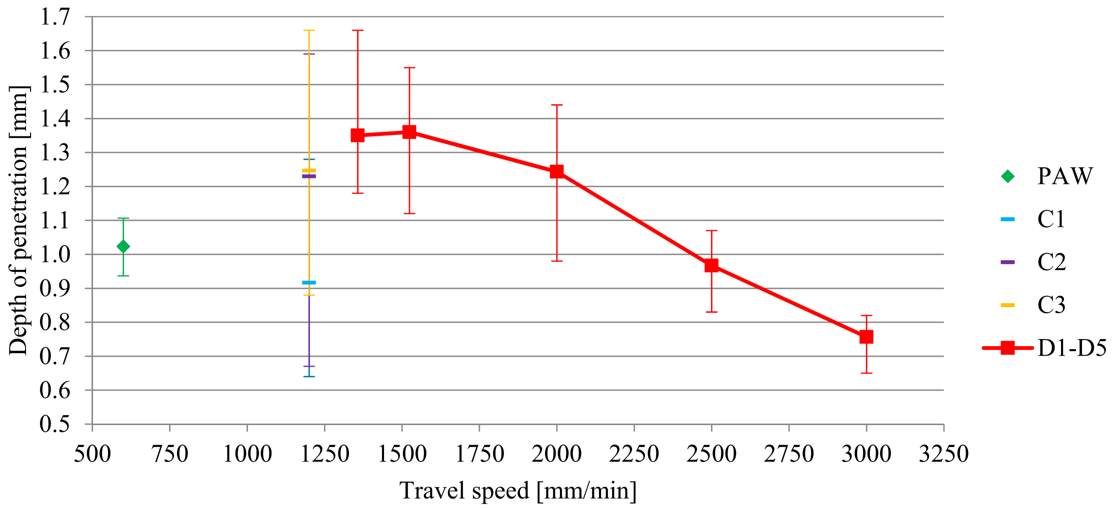

Fig. 9. The average depth of penetration measured for each cut sections in Fig. 5, 6 and 7 is shown by the marker. For each marker the error bar shows the lowest and highest depths of penetrations measured.

The laser conduction welding results in cross sections similar to those seen with PAW. Both processes primarily rely on the conduction of heat from the surface melt through the sheets. As a result, the welds are inverted bell shaped with large relative differences of the weld depth between the center and the outer seams. To reach the required depth at the outer seams, low welding speeds must be applied. This may result in an unnecessary depth of the weld in the center seam and thus an unnecessary heat input. Also, due to the uncertainty as to the sizes of the groove gaps between the sheets, the welds seem to tilt randomly towards one side, resulting in process instability issues.

The welds made using the 9-spot pattern show uniform depths through the full width of the weld. The uniformity remains relatively unaffected by changes in travel speed and uncertainty of groove gaps. Thus, compared to PAW and single-spot laser conduction welding, applying a DOE allows higher welding speeds and lower energy input, shown in Table 4, to reach the required weld depth; it also increases process stability.

Table 4. Line energy applied for the welding processes.

Welding process	PAW	C1, C2 and C3	D1	D2	D3	D4	D5
Line energy [J/mm)]	329	150	133	118	90	72	60

5. Conclusion and future work

A spot pattern from a single mode fiber laser with 9-spots was designed to perform welds of a part in which four sheets had to be joined in a butt-joint configuration with a depth of penetration of 1 mm and no welding defects. The designed spot pattern demonstrated that a satisfactory quality could be achieved, but further investigations must be performed since severe porosities were observed in some of the welds. It is recommended that the distance between the three outer spots and the three center spots is increased to lower the tolerance requirement of the tracing equipment. The welding speed of the laser welds performed by the 9-spot pattern and a 3 kW singe mode fiber laser can be about 3 times faster than the speed achieved in the current production, which applies a PAW process. The reliability of the depth of penetrations for the 9-spot laser welding process indicates that welding with a 9-spot pattern is a suitable substitute for the PAW process.

Acknowledgements

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References

Abt, F., Hess, A., Dausinger, F., 2007, Focusing of high power single mode laser beams, ICALEO2007.

Brian, Victor M., (2009), Custom beam shaping for high-power fiber laser welding, Master thesis Ohio State University.

deGraaf M., Aarts R., Jonker B., Meijer J., 2010, Real-time seam tracking for robotic laser welding using trajectory-based control, Control Engineering Practice 18 (2010), page 944–953.

Hansen, K. S., Kristiansen, M., Olsen, F.O., 2014, Beam shaping to control of weldpool size in width and depth, Physics Procedia 56 (2014) 467 – 476

Hansen K. S., Olsen F. O., Kristiansen M., Madsen O., 2015a, Joining of multiple sheets in a butt-joint configuration using single pass laser welding with multiple spots, Journal of Laser Applications, Vol. 27, Number 3

Hansen, K. S., Olsen, F. O., Kristiansen, M., Madsen, O., 2015b, Multispot Laser Welding to Improve Process Stability, In Lasers in Maufacturing 2015

He X., 2012, Finite Element Analysis of Laser Welding: A State of Art Review, Materials and Manufacturing Processes, 27: 1354–1365, 2012

Luo Z., Dai J. S., Wang C., Wang F., Tian Y., Zhao M., 2012, Predictive seam tracking with iteratively learned feedforward compensation for high-precision robotic laser welding, Journal of Manufacturing Systems 31 (2012), page 2–7.

Salminen, A., Westin, E., Lappalainen, E., Unt, A., 2012, Effect of Gas Shielding and Heat Input on Autogenous Welding of Duplex Stainless Steel, ICALEO2012

Sundqvist J., Kaplan A.F.H., Shachaf L., Brodsky A., Kong C., Blackburn J., Assuncao E., Quintino L., 2016, Numerical optimization approaches of single-pulse conduction laser welding by beam shape tailoring, Optics and Lasers in Engineering 79 (2016) 48–54.

Trautmann, A., Roeren, M., Zaeh, M.F., 2004, Welding of extruded aluminium profiles by a hybrid bifocal laser system, Laser Assisted Net Shape Engineering 4, LANE2004

Verhaeghe, G., Hilton, P., 2005, The effect of spot size and laser beam quality on welding performance when using high-power continuous wave solid-state lasers, ICALEO2005

Yu-Ning Liu, 1995, Thermal analysis of multiple beam laser welding, PhD dissertation, The University of Michigan, 1995.